IN-20
168982
p. 40

NASA
Technical
Memorandum

NASA TM - 108406

DESIGN VERIFICATION TEST MATRIX DEVELOPMENT FOR THE STME THRUST CHAMBER ASSEMBLY

Carol E. Dexter, Sandra K. Elam, and David L. Sparks

Propulsion Laboratory
Science and Engineering Directorate

June 1993

(NASA-TM-108406) DESIGN VERIFICATION TEST MATRIX DEVELOPMENT FOR THE STME THRUST CHAMBER ASSEMBLY (NASA) 40 p

N93-27251

Unclas

G3/20 0168982

National Aeronautics and
Space Administration

George C. Marshall Space Flight Center

REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	June 1993	Technical Memorandum

4. TITLE AND SUBTITLE

Design Verification Test Matrix Development for the STME Thrust Chamber Assembly

5. FUNDING NUMBERS

6. AUTHOR(S)

C.E. Dexter, S.K. Elam, and D.L. Sparks

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

8. PERFORMING ORGANIZATION REPORT NUMBER

[illegible]

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM - 108406

11. SUPPLEMENTARY NOTES

Prepared by Propulsion Laboratory, Science and Engineering Directorate.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified—Unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This report presents the results of the test matrix development for design verification at the component level for the National Launch System (NLS) space transportation main engine (STME) thrust chamber assembly (TCA) components, including injector, combustion chamber, and nozzle. A systematic approach was used in the development of the minimum recommended TCA matrix, resulting in a minimum number of hardware units and a minimum number of hot fire tests.

14. SUBJECT TERMS

STME, combustion devices, development testing, thrust chamber assembly

15. NUMBER OF PAGES 40

16. PRICE CODE NTIS

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

DEFINITION OF SYMBOLS

ηC^*	Characteristic velocity efficiency

UNUSUAL TERMS

Taguchi	A design of experiments method, named after Genichi Taguchi, which focuses on orthogonal arrays to investigate hardware operation and optimization (reference 1).
Nozzle flow split	Describes the distribution of nozzle coolant mass flow rates. The first number is composed of the primary cooling injected into the chamber through supersonic injectors located along the nozzle wall, and the convective flow through the nozzle cooling tubes. The second number is the secondary cooling which is injected subsonically just upstream of the supersonic injectors. Testing will determine the flow split between the primary and convective flow circuits.

ABBREVIATIONS

Accel	Accelerometer
ADP	Advanced development phase
AF	Air Force
ASI	Augmented spark igniter
CAT	Flow straightener
CC	Combustion chamber
CPIA	Chemical Propulsion Information Agency
Diff.	Differential
DOX	Design of experiments
DVP	Design verification phase
F	Filter
FE	Flowmeter
Freq	Frequency
GH_2	Gaseous hydrogen
HV	Hand valve
Inj	Injector
Isp	Specific impulse
LH_2	Liquid hydrogen
lox	Liquid oxygen
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NLS	National Launch System
O/F	Mixture ratio
P	Pressure
Pc	Chamber pressure
PCV	Pressure control valve

ROV	Remote operated valve
RO	Orifice
RTD	Resistance temperature device
SSME	Space shuttle main engine
STME	Space transportation main engine
STR	Strainer
T	Temperature
TCA	Thrust chamber assembly
Temp	Temperature
TS	Test stand
VM	Venturi
XCV	Control valve

TECHNICAL MEMORANDUM

DESIGN VERIFICATION TEST MATRIX DEVELOPMENT FOR THE STME THRUST CHAMBER ASSEMBLY

SUMMARY

The purpose of this study is to define the minimum number of tests required to demonstrate that the design, manufacturing, performance, and operability goals for the space transportation main engine (STME) injector, combustion chamber, and nozzle have been successfully achieved. The systematic approach used in the development of the minimum recommended thrust chamber assembly (TCA) component-level matrix included: definition of the objectives and requirements, identification and classification of the test matrix variables, determination of the test facility capabilities, performance of an error and uncertainty analysis, definition of the appropriate design of experiment methods, and definition of the hot fire test matrix.

INTRODUCTION

The STME is a 650,000 lbf (2,891 kN) thrust gas-generator cycle engine under development for the joint NASA/Air Force National Launch System (NLS) family of vehicles. Development of STME components relies on a systematic approach using subscale and full-scale component design and test. Program goals in cost, reliability, and operability must be met while achieving acceptable engine performance. Hardware development cost plays an important role in the overall engine cost. For this reason, development of the components requires a well-thought-out test plan to ensure that the engine design and operational requirements are validated with a minimum number of hardware units and a minimum number of tests.

TEST OBJECTIVES AND REQUIREMENTS DEFINITION

The objectives of the STME TCA component development tasks are to ensure that the low cost and performance goals for the components have been successfully met. Success will be measured by the adherence to the requirements established by the Contract End Item[2] and the engine Interface Control Document.[3]

Development of the components will be accomplished in two phases: the advanced development phase (ADP) and the design verification phase (DVP). The ADP precedes the DVP. During the ADP testing phase, a variety of hardware designs may be tested, and the optimum hardware design must be determined. The component design chosen during the ADP must be verified during DVP testing. Following DVP testing, the components must undergo engine systems testing for requirements verification which cannot be met at the component level. Table 1 gives a description of the development phases. This report will address only the DVP component level test matrices.

The verification requirements were identified from a number of NLS program documents[2,3] and were classified according to where they could be met with minimum risk, minimum cost, and maximum success. Analysis, bench or lab, subscale, component, and engine system level testing were all considered. Analysis is defined as any computer model, calculation, or review of an experience base. Bench or lab is defined as any proof test, flow test, manufacturing process demonstration, or physical model demonstration of a design feature. Subscale is defined as a smaller than full-scale size component level test. Component refers to full-scale component testing, and engine refers to engine system testing.

Injector requirements are summarized in table 2, chamber requirements are summarized in table 3, and nozzle requirements are summarized in table 4. In many instances, the objective may be met at a variety of different test levels. Any requirements which can be met prior to the engine systems level lower the overall cost and risk. Although subscale or component testing may provide preliminary verification of many requirements, engine systems testing must provide the final verification, since it is generally impossible to completely simulate all the interfaces and operational characteristics of the engine system at the subscale or component level.

The identified requirements which need verification at the component level are defined as follows:

Stability: The injector and chamber designs should support stable combustion and dynamic stability as specified by the requirements defined in the draft Contract End Item Specification.[2]

Combustion Efficiency: The injector and chamber designs should support the engine's required characteristic velocity efficiency, ηC^*, as defined in reference 2.

Chamber Thermal Performance:

Wall Temperatures—The coolant channel design of the chamber's liner must maintain wall temperatures and gradients at acceptable levels (to prevent wall deterioration) during all modes of operation.

Chamber Coolant System (Pressure Drop/Flow Rate/Uniform Distribution)—The coolant system design should allow uniform coolant distribution and minimal pressure drop through the liner, while providing an adequate coolant flow rate for maintaining acceptable wall temperatures.

Adequate Regenerative Cooling—The regenerative cooling exiting the chamber should be at the required state (temperature, pressure, enthalpy) necessary to support the injector mixer requirements.

Contamination Effects—The chamber's thermal performance and cooling effectiveness should not diminish beyond acceptable limits due to propellant foreign particle contamination of a specified size and quantity. (Contamination control could be provided through cleanliness specifications, inspections, and/or use of a filter.)

Nozzle Thermal Performance:

Nozzle Cooling Performance—Cooling for the nozzle is provided by both protective film flow and convective heat transfer. A percentage of the turbine exhaust gas is introduced into the nozzle by the primary film injector. This assembly provides uniform circumferential injection of the hydrogen rich exhaust gas in close proximity and parallel to the nozzle wall. A much smaller percentage of the gas is injected into the nozzle just upstream of the primary injector to keep the primary injector from overheating. The remainder of the gas flows down the center of the tubes which comprise the nozzle skirt, providing additional backside convective cooling to the nozzle walls. The combination of the three cooling flows must maintain wall temperatures and thermal gradients at acceptable levels to prevent wall deterioration during all modes of operation. (Note: An absolute assessment of cooling performance can only occur at the engine level. There are currently no facility provisions which support cooling the nozzle with gas that exactly represents turbine exhaust. The nozzle will be cooled during component level tests with ambient hydrogen.) The coolant system design should produce uniform coolant distribution and exhibit the designed pressure drop through the film coolant circuit and nozzle skirt tubes.

Chamber Wall Compatibility: The chamber wall materials should be compatible with the coolant and the combustion products and should not degrade unacceptably due to engine operations. The injector should not produce unacceptable wall streaking, which would degrade the chamber's thermal performance. The effects of wall compatibility methods and excursions in mixture ratio should be demonstrated during all modes of operation.

Structural Integrity: The injector, chamber, and nozzle should withstand steady and dynamics loads (with appropriate safety factors as defined in reference 2) during all modes of operation.

Interfaces: The integrity of the injector/chamber and chamber/nozzle interfaces should remain intact under steady, dynamic, and thermal loads during all modes of operation. The interface must remain compliant between the cryogenically cooled chamber and the relatively hot turbine exhaust cooled nozzle. Any mechanical discontinuities at the interfaces should not perturb the core flow to the extent of initiating locally high heating rates or degrading performance. (Note: Current test facility capabilities limit TCA run times to approximately 8 s. Analysis by the nozzle contractor indicates that this is insufficient time to achieve steady-state thermal conditions for the nozzle. Therefore, acceptance criteria for this phase of testing may be somewhat different than for engine level.)

Tables 5, 6, and 7 present the component test variables used to investigate the injector, chamber, and nozzle operational requirements.

TEST MATRIX VARIABLE IDENTIFICATION

To meet the desired test requirements at the DVP, a number of parameters could be varied. These parameters were identified by members of the component development teams. Independent parameters are the input or test controllable variables. Dependent variables are the output or monitored variables. Each parameter was classified into either the independent or dependent category. Test facility capabilities and limitations also played a role in the final determination of the parameters which would be deliberately varied during testing. Occasionally, a parameter could not be varied due to test facility limitations. Figures 1, 2, and 3 present the injector, chamber, and nozzle dependent and independent variables.

The ranges over which testing should take place were chosen based on expected operating ranges in the STME power balance 26b.[4] The engine is expected to operate at a 70-percent throttle point and at nominal mainstage. Due to the inability to completely control flight effects, operation of the components must also be validated at flight effects conditions. Component-to-component variation leads to a predicted 3-sigma variation in the operating box for the components. These values were also taken into account when choosing the component operating ranges. The minimum test condition was defined as the 70-percent throttle value –3-sigma. The maximum test condition was defined as the flight effects value +3-sigma. Tables 8, 9, and 10 present the injector, chamber, and nozzle power balance minimum and maximum conditions.

TEST FACILITY CAPABILITY DETERMINATION

At this time, two test facilities are under consideration for hot fire testing of the TCA hardware: the MSFC TS116 750K position (750,000-lbf or 3,336-kN thrust), and the AF Phillips Lab 2A position. The MSFC TS116 750K position is currently designed for injector and combustion chamber testing only. Facility modifications would be required to support testing with a full-scale nozzle. The AF Phillips Lab 2A position is still under construction. Schematics of the facilities are shown in figures 4, 5, 6, 7, and 8.

Test facility capability evaluation included: identification of parameters which could be varied successfully on the test stand, definition of the maximum run time, and evaluation of existing instrumentation and instrumentation requirements. The test facility capabilities were important in determining the number of data points which could be collected in a single test. Table 11 presents the facility instrumentation error estimates for the MSFC TS116 750K position.

Facility Control Parameter Identification

Limitations in test facility capabilities have an effect on the parameters which may be varied during a hot fire test. For example, at both MSFC TS116 and Phillips Lab 2A, the lox temperature may not be deliberately controlled, and there are currently no capabilities to simulate the hot turbine exhaust gas required for nozzle cooling. The ability to control lox temperature is not a significant requirement, and all test objectives may still be met without variation in the lox temperature. Nozzle cooling evaluation is a critical test objective, and using ambient temperature hydrogen for nozzle cooling will only allow partial evaluation of the test objectives. Propellant flows are controlled by pressurization of the propellant run tanks on both the test stands. To change either the chamber pressure or the mixture ratio, the propellant flow rates must be changed by increasing or decreasing the tank pressures. The ability to change the propellant tank pressures during a test is unlikely to exist. No other significant test facility limitations were identified.

Maximum Run Time Definition

The maximum run time for each of the test facilities is only an estimate at this time. The MSFC 750K position mainstage duration is estimated to be 8 s. This duration is limited by the GH_2 pressurization to the LH_2 tanks. The AF Phillips Lab 2A position mainstage duration is estimated to be 9 s. This duration is limited by the LH_2 capacity. Neither test stand has a duration long enough to allow the nozzle to come to thermal equilibrium, therefore engine systems testing will be required to meet some of the nozzle test objectives. These test durations are also not long enough to permit testing at more than one chamber pressure, mixture ratio, or fuel temperature.

Instrumentation Definition

Identification of the instrumentation measurements included: definition of the facility and test article instrumentation locations, and determination of the range, quantity, and accuracy. See the facility schematics for locations of the facility instrumentation. Preliminary component instrumentation recommendations are presented in tables 12, 13, and 14. In many instances, additional instrumentation was requested by various technical disciplines, but due to the difficulty in providing that instrumentation, it has not been included. Information on the range and accuracy of the instrumentation has not been included in this report.

Error and Uncertainty Analysis Development

If the effects of a planned input change cannot be seen in the output, due to error and uncertainty, there is no point in running the test. Likewise, if a change in operation is observed, the cause for that variation must be understood. For these reasons, understanding the error and uncertainty in the data measured and any calculated parameters are critical. A detailed error and uncertainty analysis as described in reference 5 has not been completed and will be reported at a later date.

Definition of existing facility instrumentation was the first step in determining the effects of bias (fixed) and precision (random) errors in the test measurements. In addition to error in instrumentation, a number of uncertainties affect the calculation of output parameters. These error factors are identified in tables 15, 16, and 17. Understanding the significance of the effects of these uncertainties is required for the error and uncertainty analysis.

EXPERIMENTAL TECHNIQUES IDENTIFICATION

Design of Experiments Methods

A variety of design of experiments (DOX) methods are appropriate for component level testing, including: one factor at a time, full factorial, and Taguchi. As the test matrices were developed, the pros and cons of the various DOX methods were evaluated to determine which technique would best suit the test objectives and requirements. The one factor at a time technique minimizes the number of tests, but provides unbalanced parameter coverage. The full factorial method tests all combinations of parameter levels, therefore resulting in a large number of tests. The Taguchi method provides balanced parameter coverage, therefore minimizing error bands on sensitivities and minimizing the number of tests.

Experimental Techniques Selection

Eight parameters were identified as the independent variables to be varied during TCA testing. They are: Pc, O/F, injector fuel temperature, combustion chamber inlet pressure, combustion chamber coolant flow rate, combustion chamber coolant inlet temperature, nozzle coolant flow rate, and nozzle flow split. Three levels of testing were initially identified: throttle, mainstage, and flight effects. If one factor were varied at a time over the range of operating conditions (including the 3-sigma variations), the test matrix would be unnecessarily large. Many of these component parameters can in fact be varied without impacting the operation of the other components. For example, changing the nozzle coolant flow rate has no impact or effect on the chamber coolant flow rate. The independence of many of these parameters makes the use of the Taguchi DOX methodology particularly useful. If interactions between parameters are understood, then they can be taken into account when designing the Taguchi experiment. If a linear relationship exists between the input and output parameters, then only two levels need to be tested. Nonlinearity of parameters requires that at least three levels be tested. Analysis of results from a three-level matrix can be very difficult, and it is usually better to avoid this type of test matrix if possible. The TCA operating range of most concern is around the nominal point. The relationships between input and output parameters are expected to be linear from the nominal –3-sigma to the nominal +3-sigma range. For these reasons, the Taguchi method was chosen for evaluation of the nominal operating range. Repeating the entire Taguchi matrix at the throttle and the flight effects conditions would result in an unjustifiably large number of extra tests, therefore single tests at the actual throttle point, throttle point –3-sigma, and flight effects condition were chosen.

One of the primary test objectives for the TCA is to understand the stability characteristics of the injector design. Interactions between parameters are not well understood in the stability area. The only parameters of interest for stability testing are: Pc, O/F and injector fuel temperature. Due to the low number of test variables and the lack of understanding of parameter interactions, the one factor at a time technique was chosen for the injector stability test matrix.

COMPONENT LEVEL TEST MATRIX DEFINITION

Application of Selected Experimental Techniques

Eight parameters or factors where chosen as the variables for the Taguchi matrix. In addition, four interactions were identified. The parameters and their levels are presented in table 18. The level 1 values listed in table 18 are lower risk values, level 2 are higher risk. This matrix evaluates TCA operation around the nominal operating point only. Had the factor ranges covered the throttle-to-flight effects range, linearity of the parameters could not have been assured, and at least three levels would have been required. An L16 matrix is required to test eight parameters. Traditional Taguchi methods were used to assign the factors to the appropriate columns. Some factors lead to higher risk hardware conditions. In these cases, the lower risk factors were assigned to columns where they would be tested at both level 1 and level 2, while a higher risk factor remained at level 1. For example, increasing the Pc is generally riskier to the hardware than increasing the O/F. As table 19 shows, testing at both O/F levels will be conducted at the level 1 Pc before proceeding to the level 2 Pc.

The factor levels were replaced with the actual parameter values, and the interaction columns were eliminated from the matrix presented in table 20. This is the preliminary TCA test matrix. Interaction columns are eliminated from the matrix because they cannot be set, but rather fall out from the setting of the factors which make up the interaction. When the test data are analyzed, the interaction columns must be put back into the proper location in the matrix.

Since the Taguchi matrix does not include testing at the actual nominal, throttle point, or flight effects conditions, additional testing is required to meet all the DVP requirements. Single test points at the throttle, throttle –3-sigma (expected minimum), nominal, and flight effects +3-sigma (expected maximum) are expected to be sufficient to allow evaluation of component operation.

Prior to stability testing, the optimum bomb size must be determined. The bomb detonation must result in sufficient overpressures without damaging the chamber. In the past, there have been cases where a smaller grain bomb has resulted in a combustion instability, whereas a larger grain bomb has not. For this reason, multiple bomb sizes must be detonated. An estimated 10 tests are required to evaluate the appropriate bomb grain size. The preliminary injector TCA stability test matrix is presented in table 21. The tests were planned beginning with low risk conditions (low Pc, low O/F, high fuel temperature) and proceeding to high risk conditions (higher Pc, higher O/F, lower fuel temperature). The range of values tested covers the same range as identified in table 18.

Number of Units

In addition to development of the test matrix, the number of units for testing was also investigated. A technical justification for testing more than one unit is required. Simply using past development programs for that justification is unacceptable. The more critical a parameter is to the overall success of the engine system, the more it needs to be tested or investigated. If any parameter is so important that the gas generator cycle or the engine design itself cannot operate with variation in that parameter, then unit-to-unit variation may be very significant. If the engine system can tolerate a large variation in operation of a given parameter, then the unit-to-unit variability is not significant.

Engineering judgment was used to evaluate the critical TCA verification requirements. Only those requirements with small or no margins require testing of multiple units. Injector ηC^* performance and stability were the only requirements identified as capable of making or breaking the engine operation. If overall engine specific impulse (Isp) is not high enough, then the engine is incapable of launching the required payload. Injector instability problems could result in a total injector redesign, resulting in significant program cost and schedule impacts. Although all other requirements are important, they were not identified as being real show stoppers.

The STME power balance 26b[4] assumes a 3-sigma percent variation in ηC^* of ± 0.375 percent. If a unit-to-unit variation in ηC^* larger than 0.375 percent is seen, then injector performance differences are unacceptable and further work must be done to reduce the component variability. To determine if multiple injectors must be tested to assess this variability, a simplified analysis of the errors in measuring ηC^* from hot fire data was conducted. If the errors in the calculation of ηC^* exceed the ± 0.375-percent variation, then testing multiple units would not be beneficial. It would be impossible to determine if the variation seen was due to the errors or the differences in the units. Assuming reasonable errors for the parameters used to calculated ηC^*, a variation of 3 percent (+1 percent, –2 percent) was calculated. This value is much greater than 0.375 percent, therefore testing multiple units to determine unit to unit variation in ηC^* is not recommended. See the appendix for the analysis performed. This analysis assumed that TCA testing would be conducted at MSFC TS116 750K position. No estimates of errors in the lox and H_2 property data were taken into account during this analysis. Historical note: During SSME 40K (40,000 lbf or 178 kN thrust) testing at MSFC TS116 40K position, repeatability of ηC^* from test to test (identical test conditions, and identical hardware) was ± 0.3 percent.

Although testing will not verify the injector performance design requirement, it will provide a range of ηC^* values in which the true performance lies. If the highest ηC^* measured (taking into account the calculated error) is below the required value, then injector redesign is necessary to increase the performance. Performance verification must take place at the engine systems level.

Evaluation of the number of units to determine injector stability relied heavily on CPIA and NASA documents.[6,7] These documents present the accepted technical procedures for stability verification. A listing of the test recommendations from both the documents is presented in table 22. These recommendations were analyzed for applicability to the STME program and, in some cases, were not chosen for injector stability testing recommendations for the STME. Where the CPIA and NASA recommendations were not followed, a technical rational is given. Table 23 presents the results of this analysis.

Number of Tests

Table 24 presents the total number of hot fire tests recommended for the STME TCA component DVP testing. The Taguchi matrix presented in table 20 only takes into account testing around the nominal operating point. Before proceeding to engine system testing, TCA operation must also be verified: at the actual nominal operating point, at the throttle point, the throttle –3-sigma point (this would be the lowest operating condition), and at an 80-percent flight effects +3-sigma level (this would be a highest operating condition). Engine system evaluation predicts that the engine can correct or compensate for 20 percent of the flight effects. As a result, component operation must be verified up to the remaining 80-percent flight effects. Adding these four tests, plus an estimated six tests to check out the test stand and TCA start transient, to the injector stability matrix and the TCA Taguchi matrix, the total number of tests recommended is 66.

This number is completely success oriented and does not take into account any problems which might develop with either operation of the test stand or the TCA components. During prior test programs at MSFC, the actual number of tests conducted to complete a given test matrix has been greater than the planned number of tests. Test realization factors have been developed to account for this increase in actual test attempts, although they have not been applied to the total number of TCA tests.

CONCLUSIONS

A systematic approach was used to develop STME TCA component test matrices for verification of design requirements. An attempt was made during this activity to use strong technical justifications for determining both the number of tests and the number of units, rather than relying on number of tests in previous engine development programs. Although the authors were not comfortable with recommending only one TCA unit for testing prior to engine systems testing, they could not develop a technical justification for testing more than one unit, other than for stability verification.

Evaluation of the error and uncertainty in the test facilities proved to be significant in determining whether certain design requirements could be verified at the component level. Analyses of all design requirements based on detailed error and uncertainty analyses must be completed prior to initiation of any TCA testing. If test facility capabilities do not permit verification of the necessary design requirements, then modifications to the test facility may be necessary.

REFERENCES

1. Ross, P. J. : "Taguchi Techniques for Quality Engineering." McGraw-Hill Book Company, New York, 1988.

2. "Contract End Item Specification for the Space Transportation Main Engine Phase C/D," Draft, Rev 10, May 28, 1992.

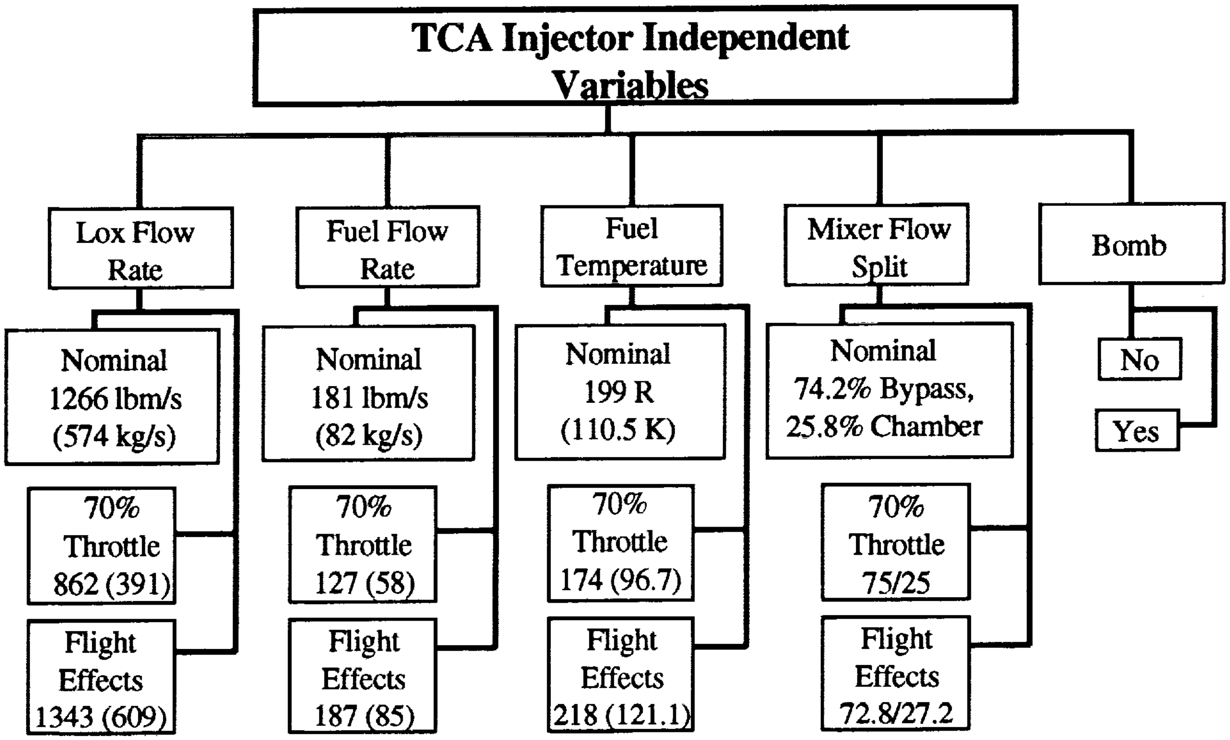
3. "Interface Control Document for the Space Transportation Main Engine/National Launch System Vehicle," Draft, Rev 6, May 28, 1992.

4. "STME Power Balance 26b," April 30, 1992.

5. Coleman, H.W., and Steele, W.G. : "Experimentation and Uncertainty Analysis for Engineers." John Wiley and Sons, New York, 1989.

6. "Combustion Stability Specifications and Verification Procedures," CPIA Pub. 247, October 1973.

7. Harrje, D.T., and Reardon, F.H.: "Liquid Propellant Rocket Combustion Instability," NASA SP-194, 1972.



70% Throttle = 70% Throttle – 3 Sigma Variation
Flight Effects = 80% Flight Effects + 3 Sigma Variation

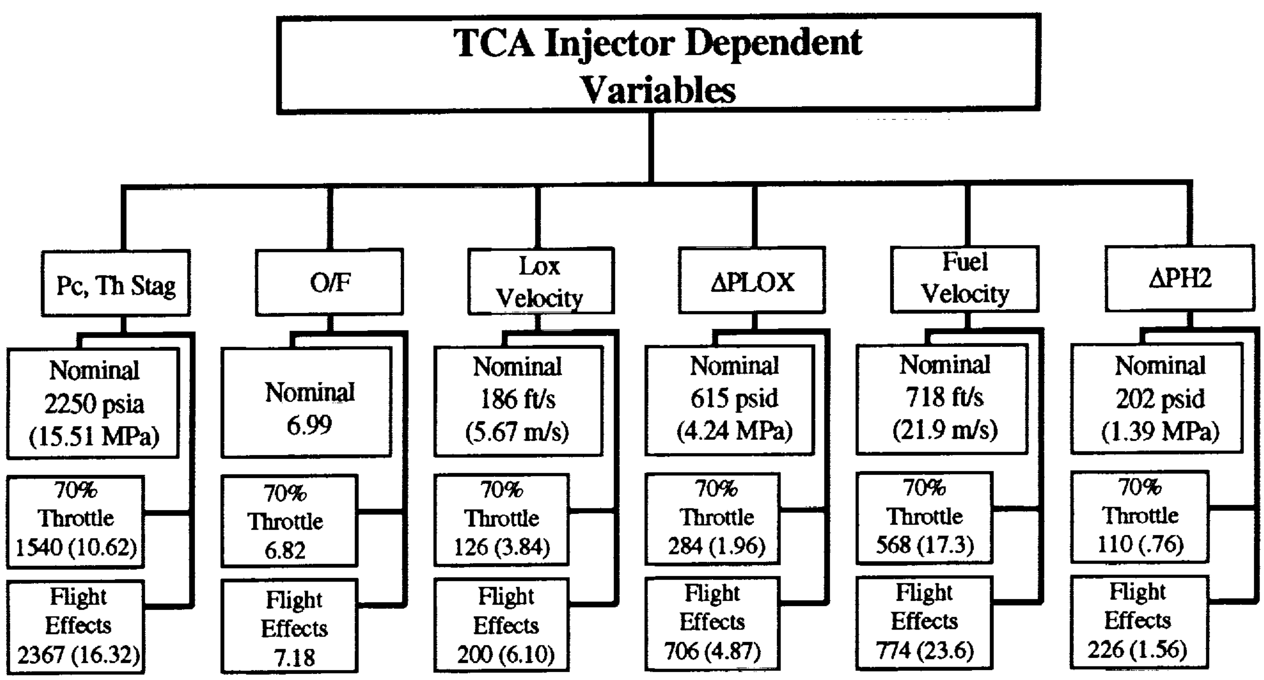


Figure 1. Injector independent and dependent variables.

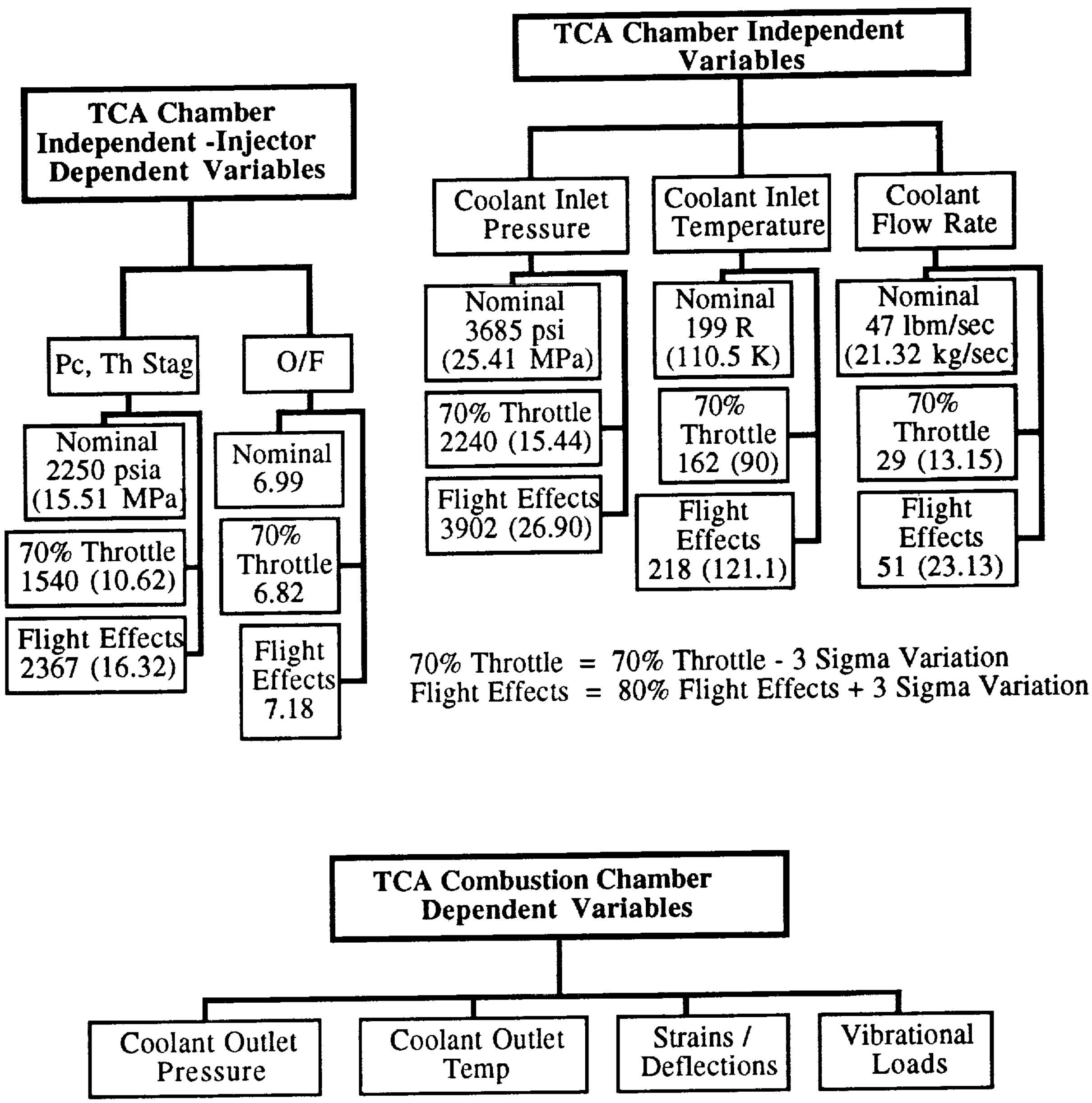


Figure 2. Combustion chamber independent and dependent variables.

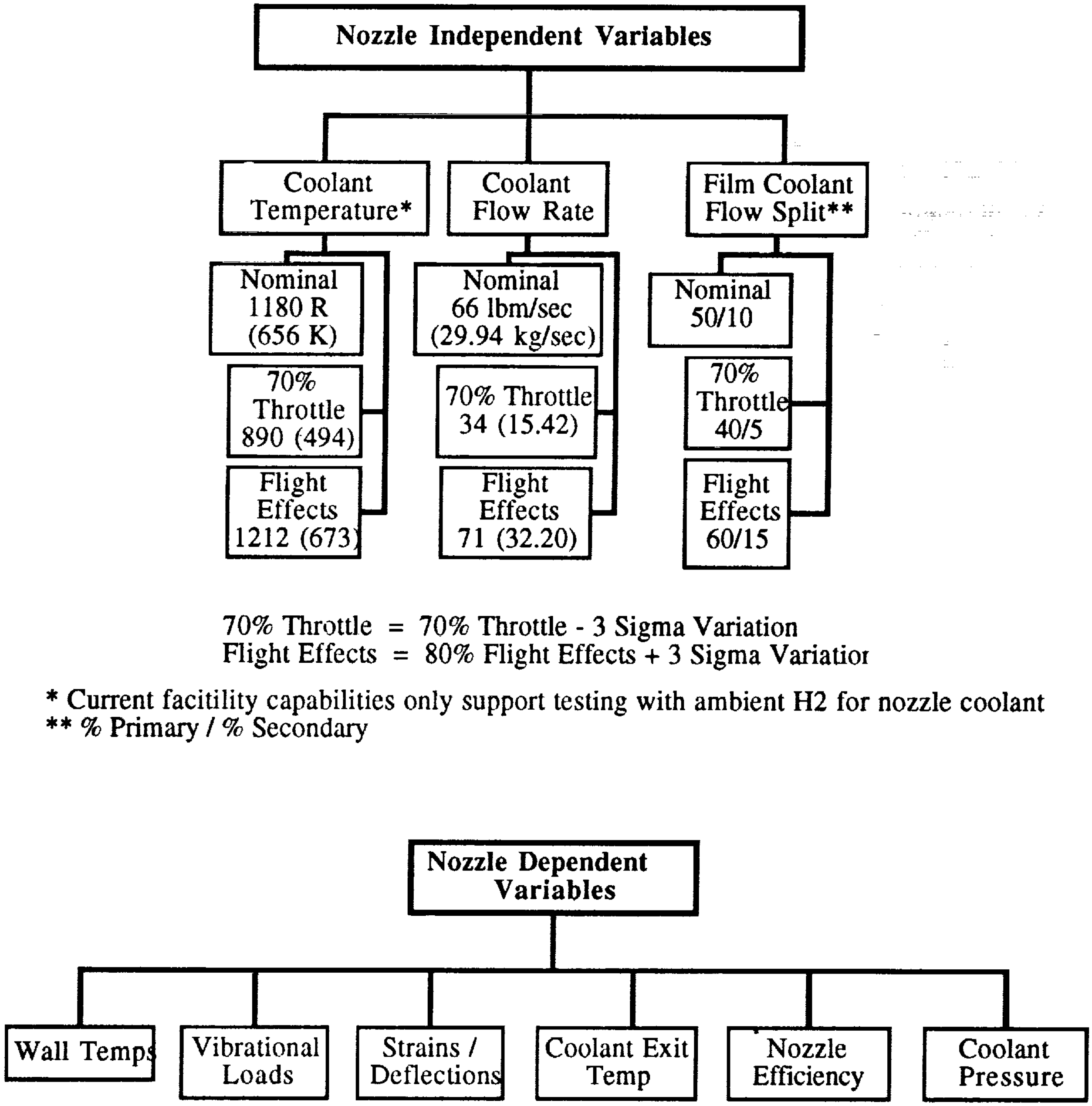
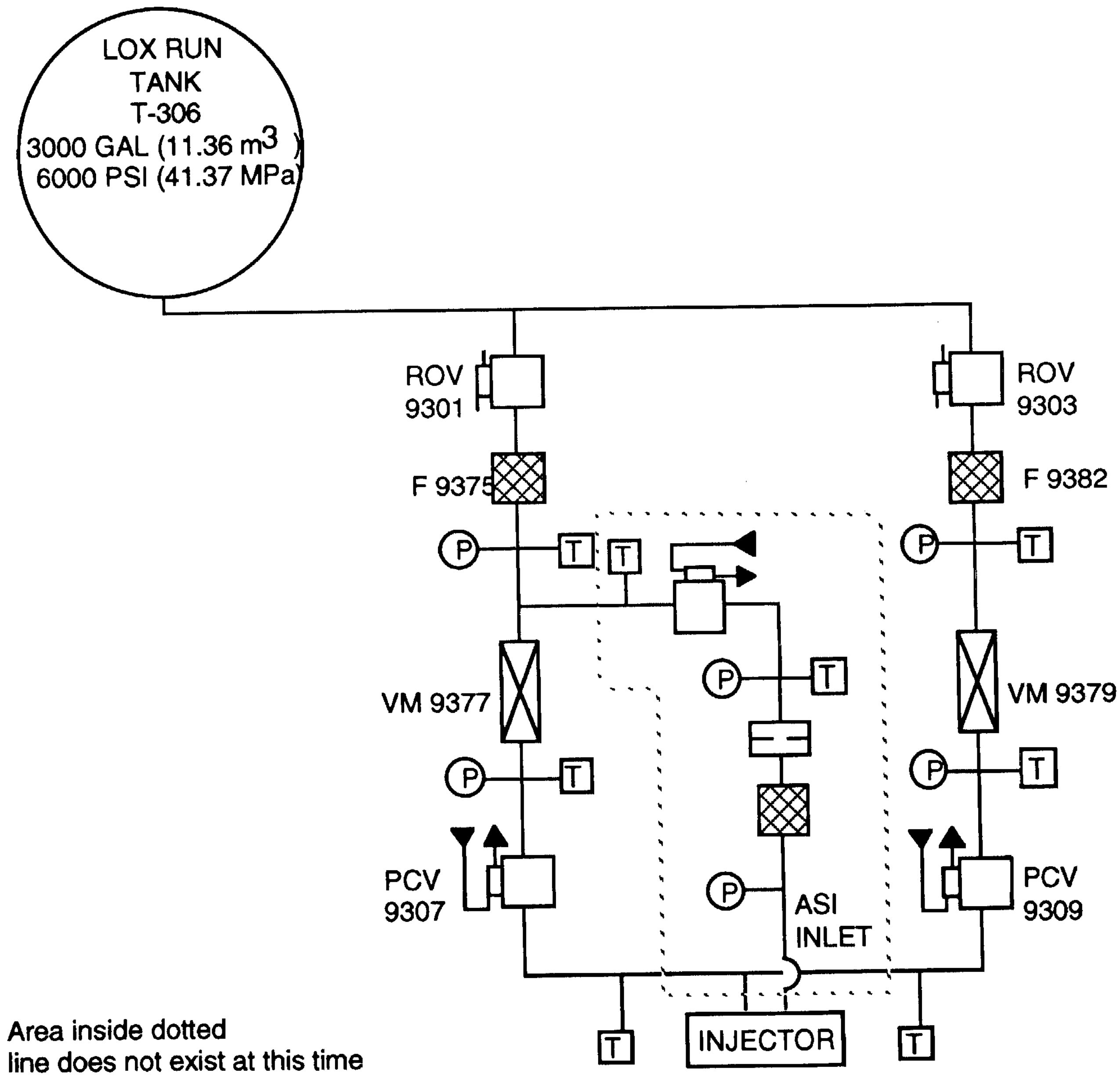
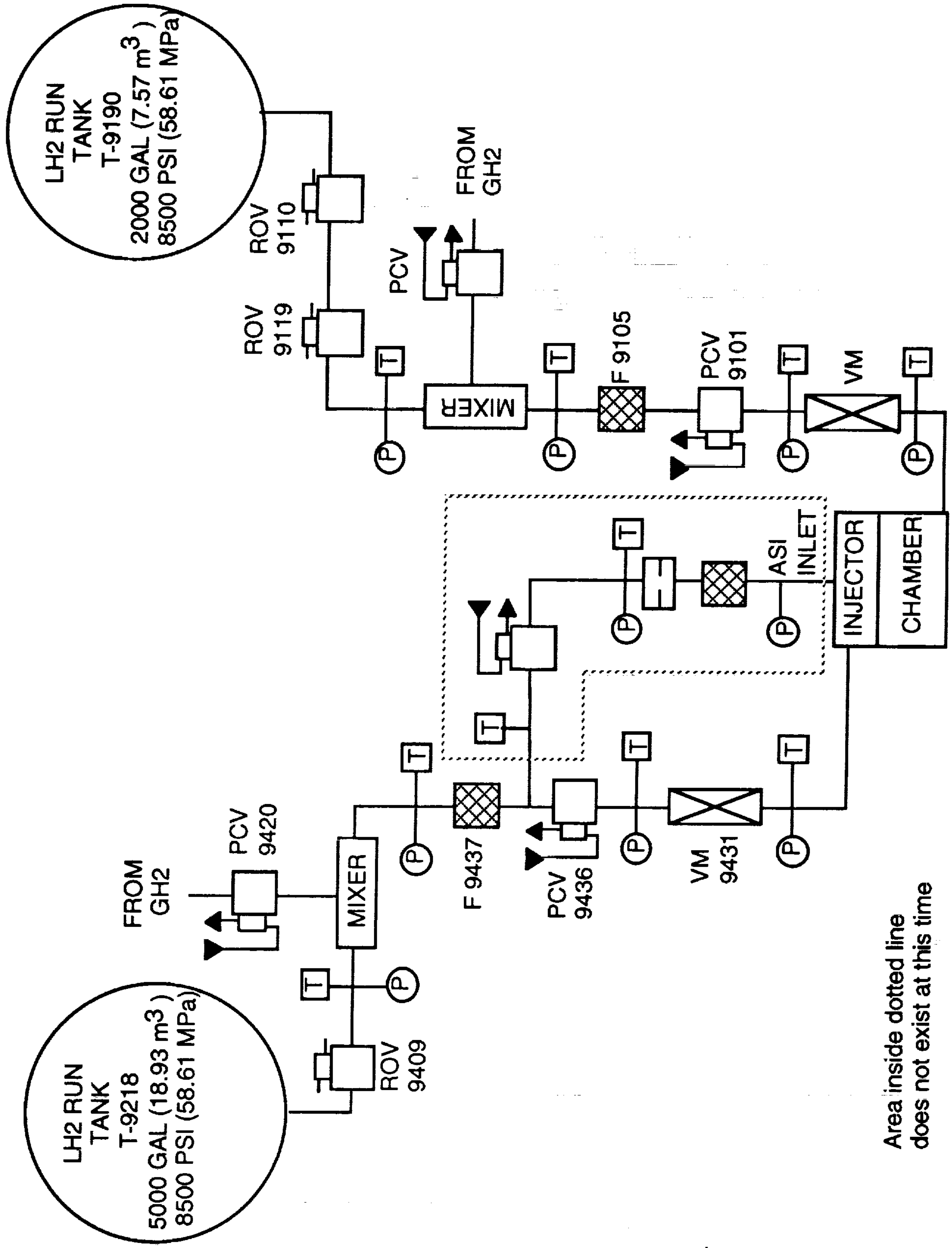


Figure 3. Nozzle independent and dependent variables.


LOX RUN
TANK
T-306
3000 GAL (11.36 m3)
6000 PSI (41.37 MPa)
ROV
9301
ROV
9303
F 9375
F 9382
P
T
VM 9377
VM 9379
PCV
9307
PCV
9309
ASI
INLET
INJECTOR
Area inside dotted
line does not exist at this time


LH2 RUN
TANK
T-9190
2000 GAL ($7.57\ m^3$)
8500 PSI (58.61 MPa)
ROV
9110
ROV
9119
PCV
FROM
GH2
MIXER
F 9105
PCV
9101
VM
T
P
INJECTOR
CHAMBER
ASI
INLET
LH2 RUN
TANK
T-9218
5000 GAL ($18.93\ m^3$)
8500 PSI (58.61 MPa)
ROV
9409
FROM
GH2
PCV
9420
MIXER
F 9437
PCV
9436
VM
9431
Area inside dotted line
does not exist at this time

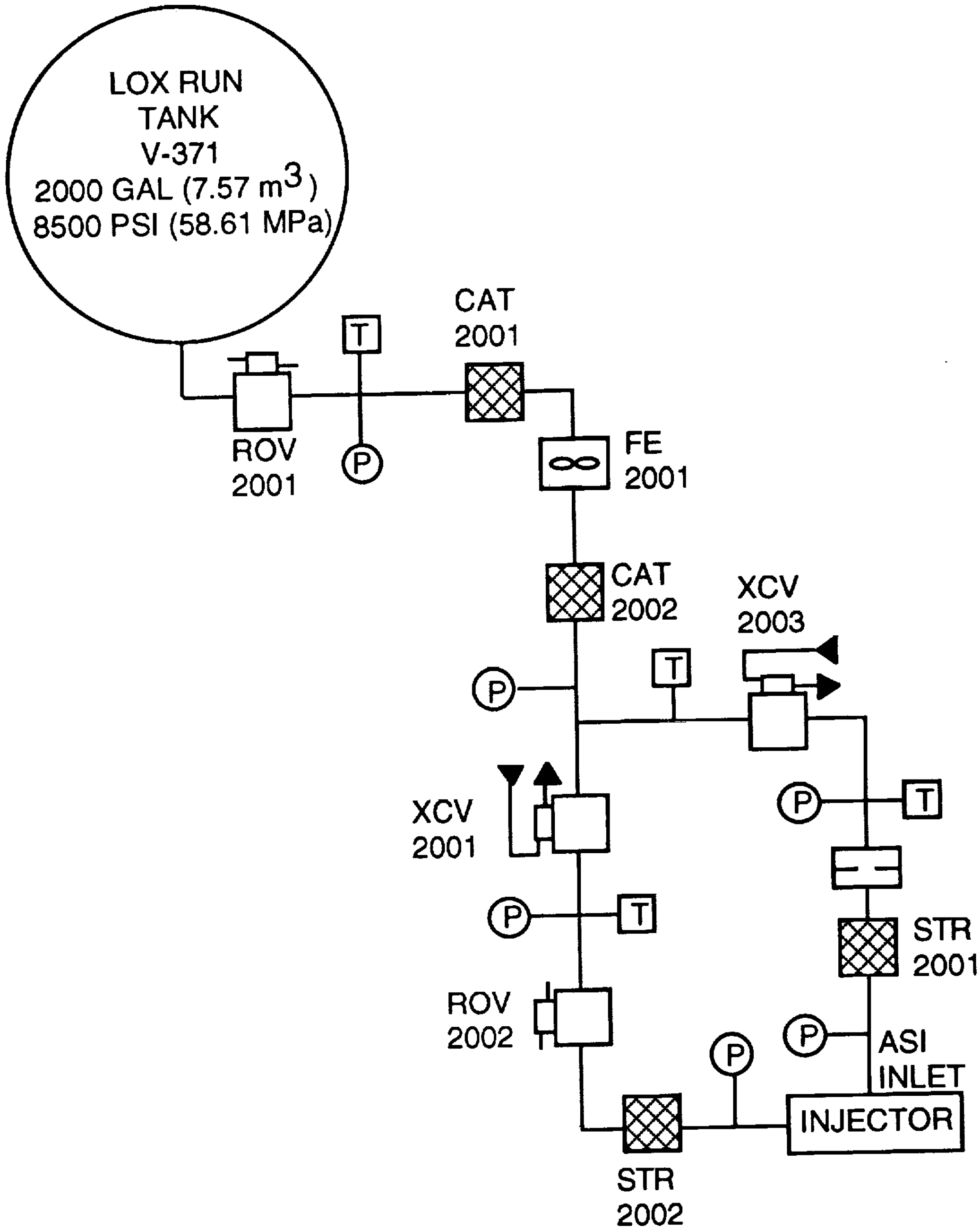


Figure 6. AF Phillips Lab 2A lox schematic.

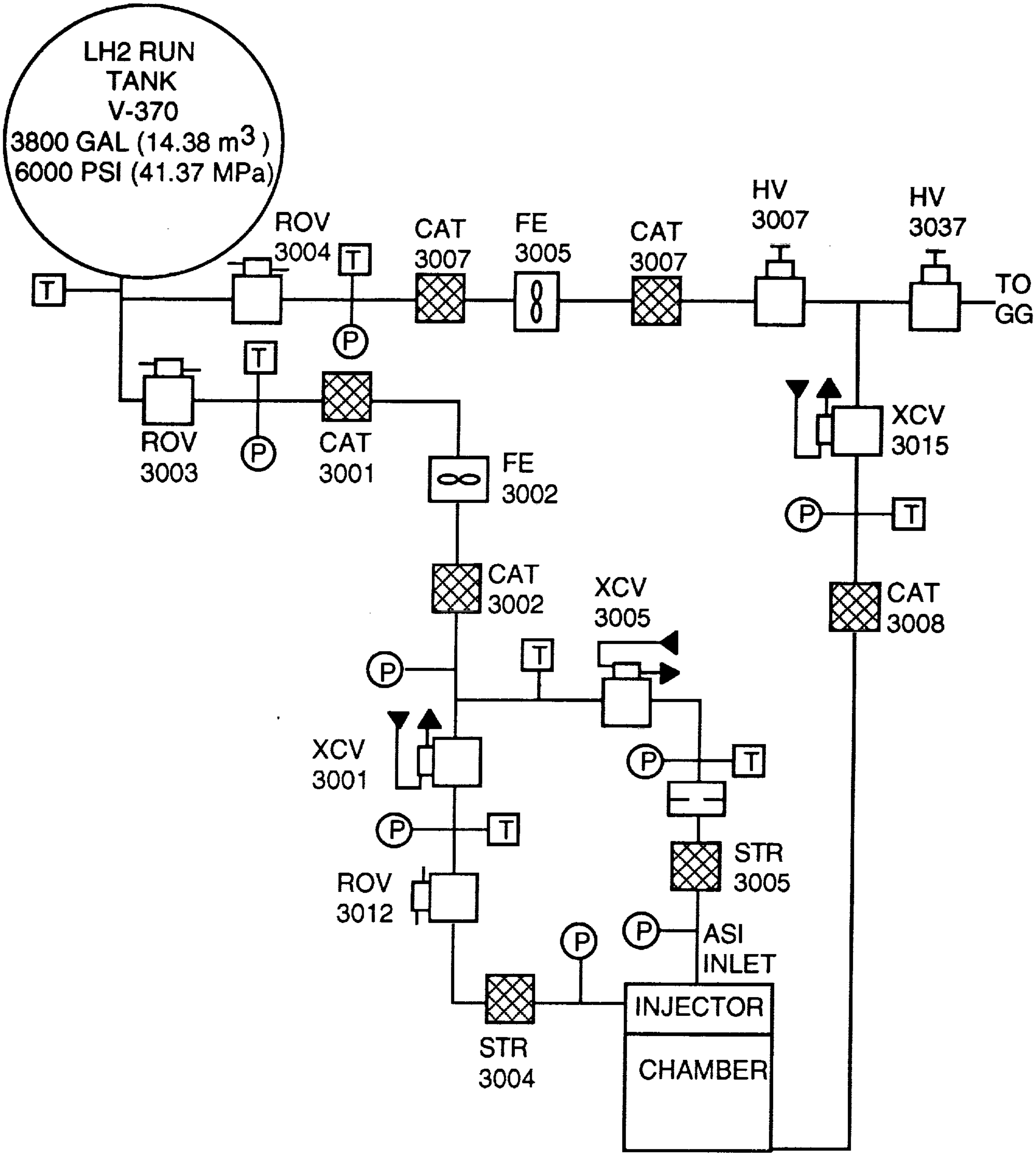


Figure 7. AF Phillips Lab 2A LH_2 schematic.

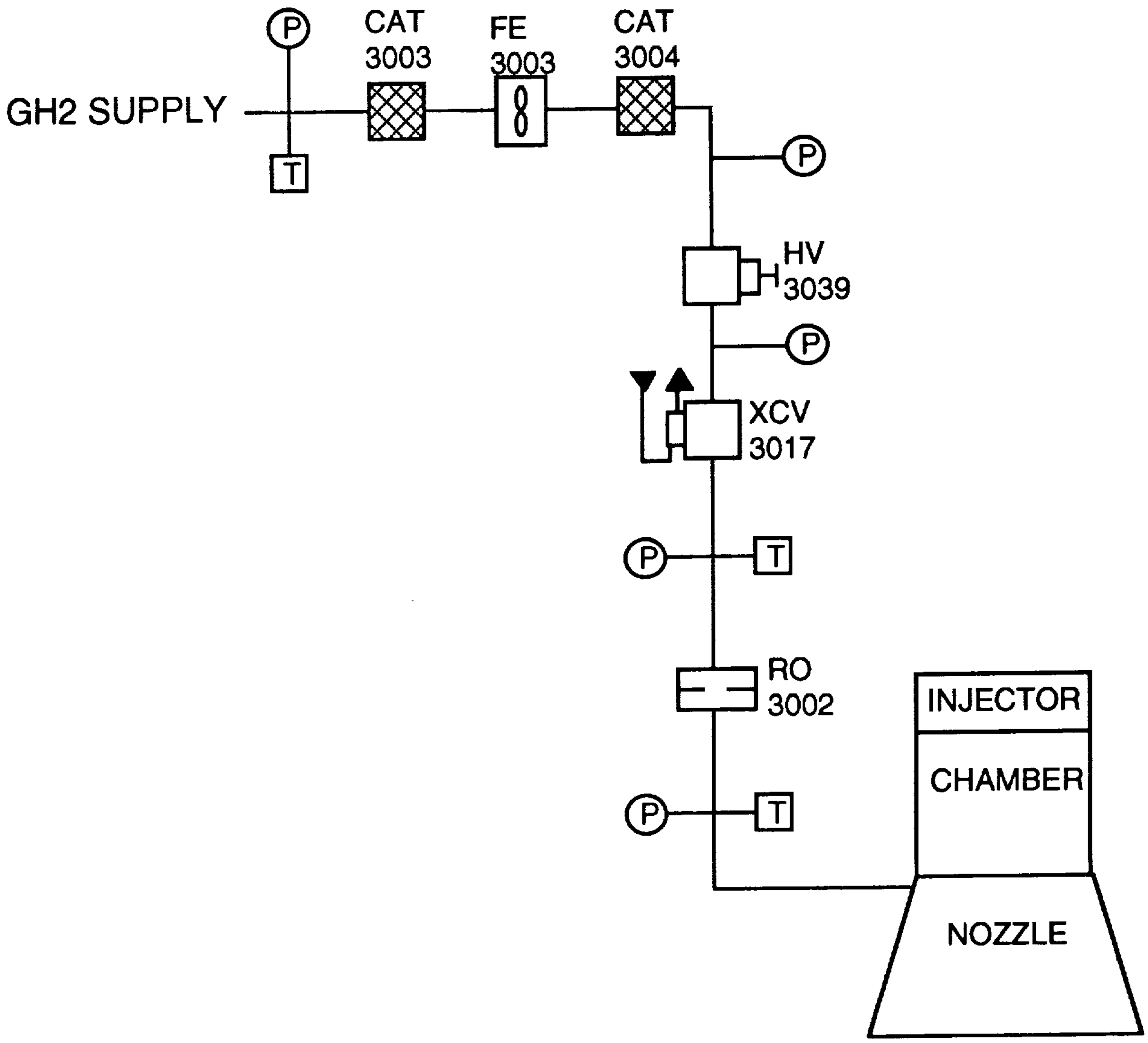


Figure 8. AF Phillips Lab 2A GH_2 schematic.

Table 1. Proposed STME development phases.

Advanced Development Phase	<u>**Analysis**</u> Any computer model, calculation, or review of an experience base	**Description:** Component efficiency, heat transfer, performance impacts due to hardware design or operation.
	<u>**Bench**</u> Proof test, flow test, manufacturing process demonstration, of a physical model	**Description:** Non-hot fire demonstration of design options
	<u>**Subscale Test**</u> Sub-scale size component level test	**Description:** Hot fire verification of design options
Development / Verification Phase	<u>**Analysis**</u> Any computer model, calculation, or review of an experience base	**Description:** Component efficiency, heat transfer, performance impacts due to hardware design or operation.
	<u>**Component Test**</u> Full scale component test	**Description:** Hot fire verification of performance, operability, structural integrity, interfaces, etc.
	<u>**Engine Test**</u> Engine systems test	**Description:** Hot fire verification at systems level of performance, operability, structural integrity, interfaces, start transient, etc.

Table 2. STME injector requirements.

Requirements	Bench Test	Subscale Test	Component Test	Engine Test
Performance – ηC^*		X	X	
High Frequency Stability – Bomb Tests – Start Transient – Mainstage Conditions			 X	 X X
Chug Stability			X	X
Wall Compatibility/Heat Transfer		X	X	X
O/F Distribution – Mixer Operation – Lox Distribution	 X 		 X X	 X X
Process Validation/Material Characterization/Weldability	X		X	
O/F and Pc Excursions		X	X	X
Start Transient Operation – Transient – Ignition			 X	 X X
Pressure Drop of Lox Post, Fuel Sleeve	X			
Structural Integrity/Joint Separation Validation/Press Diff. and Temperature Gradients			X	X
Structural Integrity/Burst Pressure Validation/Pressure – Load Proof	X			
Engine Operation Environments – Vibrations/Duration/Durability				X
Element Thermal Cycle Life/Lox Post Vibration/Reliability/Service Life/Fatigue Criteria/Effects of Combustion on Face Plate		X		X
Capability to Provide External/Internal Visual Inspection			X	X
Cleanliness/Contamination			X	X
Weight			X	

Table 3. STME chamber requirements.

Requirements	Analysis	Bench Test	Subscale Test	Component Test	Engine Test
Performance - ηC^*	X			X	X
Stability	X	X		X	X
Thermal Performance/Liner Life:	X	X	X	X	X
– Wall Temperatures	X		X	X	
– Pressure Drop	X	X	X	X	
– Coolant Flow Rate	X	X	X	X	
– Adequate Regen. Cooling	X			X	
– Uniform Coolant Distribution	X	X	X	X	
– Contamination Effects	X		X	X	
Injector Compatibility	X			X	X
– Wall Streaking	X			X	X
– Compatibility Techniques	X			X	X
– O/F Excursions	X			X	X
Structural Integrity	X	X		X	X
– Nozzle Joints	X	X		X	X
– Liner Bonds	X	X		X	X
Weight				X	

Table 4. STME nozzle requirements.

Requirements	Bench Test	Subscale Test	Component Test	Engine Test
Cooling Effectiveness / Distribution Uniformity				
– Primary Inj Orifice Size		X	X	X
– Secondary Inj Orifice Size		X	X	X
– Coolant Tube Flow Orifice Size		X		
– CC Wall O/F		X	X	X
– Coolant Flow Rate/Pressure	X	X	X	X
– Power Level		X	X	X
Side Loads – Transient				X
Nozzle ISP				
– Coolant Flow Rate/Pressure				X
– Power Level				X
Vibration Characteristics				
– Power Level			X	X
– Excitation Amplitude	X			
Gimbal Load Capability				X
Structural Integrity				
– Inlet Manifold	X		X	X
– Interface Flange Joint			X	X
– Film Injector			X	X
Tube/Jacket Bond Strength	X	X	X	X
Base Heating				X
Weight			X	

Table 5. STME injector component test variables.

Component Requirements	Pc	O/F	Fuel Temp	Bomb
Performance – ηC^*	X	X	X	
High Freq Stability – Bomb Tests				
– Mainstage Conditions	X	X	X	X
Chug Stability	X	X	X	
Wall Compatibility / Heat Transfer	X	X	X	
O/F Distribution				
– Mixer Operation	X	X	X	
– Lox Distribution	X	X	X	
Process Validation / Material Characterization / Weldability	X	X		
Start Transient Operation				
– Ignition	X	X	X	X
Structural Integrity / Joint Separation Validation / Press. Diff. & Temp. Gradients	X			

Table 6. STME chamber component test variables.

Component Requirement	Pc	O/F	Coolant Inlet Press	Coolant Inlet Temp	Flow Rate	Cycles
Performance – ηC^*	see injector					
Stability	see injector					
Thermal Performance						
– Wall Temperatures	X	X		X	X	
– Pressure Drop	X	X			X	
– Adequate Regen. Cooling	X	X	X	X	X	
– Uniform Coolant Distribution			X		X	
– Contamination Effects						X
– Liner Life						
Injector Compatibility						
– Wall Streaking			see	injector		
– Compatibility Techniques		X				
– O/F Excursions		X				
Structural Integrity						
– Nozzle Joints	X					
– Liner Bonds	X					

Table 7. STME nozzle component test variables.

Component Requirement	Pc	O/F	Coolant Inlet Press	Coolant Flow Rate
Cooling Effectiveness/Distribution Uniformity				
– Primary Inj Orifice Size	X	X	X	X
– Secondary Inj Orifice Size	X	X	X	X
– Coolant Flow Orifice Size	X	X	X	X
– CC Wall O/F	X	X	X	X
– Coolant Flow Rate/Pressure	X	X	X	X
Vibration Characteristic				
– Excitation Amplitude	X			
Structural Integrity				
– Inlet Manifold	X	X	X	
– Interface Flange Joint	X	X	X	
– Film Injector	X	X	X	
Tube/Jacket Bond Strength	X	X		

Table 8. Injector power balance minimum and maximum conditions.

Parameter Identification	Nominal	3-Sigma Variation	80-Percent Flight Effects	70-Percent Throttle
Pc, Face	2318 psi (15.98 MPa)	(±) 48 psi (0.33 MPa)	2,380 psi (16.41 MPa)	1,628 psi (11.22 MPa)
Pc, Throat Stagnation	2250 psi (15.51 MPa)	(±) 48 psi (0.33 MPa)		1,581 psi (10.90 MPa)
O/F Injector	6.99	(±) 0.116	7.06	6.94
Fuel Temp	199 R (110.6 K)	(±) 13 R (7.2 K)	205 R (113.9 K)	187 R (103.9 K)
Fuel Press	2520 psi (17.37 MPa)			1,756 psi (12.11 MPa)
Fuel Flow Rate	181 lbm/s (82.1 kg/s)			128.6 lbm/s (58.3 kg/s)
Lox Temp	180 R (100 K)			176 R (97.8 K)
Lox Press	3026 psi (20.86 MPa)	(±) 113 psi (0.78 MPa)	3,119 psi (21.50 MPa)	1979 psi (13.64 MPa)
Lox Flow Rate	1266 lbm/s (574.2 kg/s)			892 lbm/s (404.6 kg/s)

Table 9. Chamber power balance minimum and maximum conditions.

Parameter Identification	Nominal	3-Sigma Variation	80-Percent Flight Effects	70-Percent Throttle
Pc, Face	2,318 psi (15.98 MPa)	(±) 48 psi (0.33 MPa)	2,380 psi (16.41 MPa)	1,628 psi (11.22 MPa)
Pc, Throat Stagnation	2,250 psi (15.51 MPa)	(±) 48 psi (0.33 MPa)		1,581 psi (10.90 MPa)
O/F Injector	6.99	(±) 0.116	7.06	6.94
Coolant Inlet Pressure	3,685 psi (25.48 MPa)	(±) 113 psi (0.78 MPa)	3,789 psi (26.12 MPa)	2,353 psi (16.22 MPa)
Coolant Flow Rate	46.7 lbm/s (21.2 kg/s)	(±) 2.8 lbm/s (1.3 kg/s)	47.9 lbm/s (21.7 kg/s)	32.2 lbm/s (14.6 kg/s)
Coolant Inlet Temp	199 R (100.6 K)	(±) 13 R (7.2 K)	205 R (113.9 K)	175 R (97.2 K)

Table 10. Nozzle power balance minimum and maximum conditions.

Parameter Identification	Nominal	3-Sigma Variation	80-Percent Flight Effects	70-Percent Throttle
Pc, Face	2,318 psi (15.98 MPa)	(±) 48 psi (0.33 MPa)	2,380 psi (16.41 MPa)	1,628 psi (11.22 MPa)
Pc, Throat Stagnation	2,250 psi (15.51 MPa)	(±) 48 psi (0.33 MPa)		1,581 psi (10.90 MPa)
Coolant Pressure	263 psi (1.81 MPa)	(±) 18.5 psi (0.13 MPa)	289 psi (1.99 MPa)	122 psi (0.84 MPa)
Coolant Temp	1,180 R (655.6 K)	(±) 30.4 R (16.9 K)	1,212 R (673.3 K)	890 R (494.4 K)
Wall Mixture Ratio				
Film Coolant Flow Rate	66 lbm/s (29.9 kg/s)	(±) 3.6 lbm/s (1.6 kg/s)	71 lbm/s (32.2 kg/s)	33.4 lbm/s (15.1 kg/s)

Table 11. Facility instrumentation error estimates.

	MSFC TS116 750K
High Freq Press Transducer	1 percent
Pressure Transducer	0.25 percent of fullscale
RTD	± 0.05 °F
Thermocouple – Type K	± 4 °F
Flowmeter	0.5 percent

Table 12. Injector instrumentation recommendations.

	TCA Testing				
	High Freq Pressure	Static Pressure	Temp	Accel	Strain Gauge
INJECTOR					
Lox Inlet		1	1	3	X
Lox Dome, upstream of dist plate		1			
Lox Dome, downstream of dist plate	1	1			
Fuel Inlet		1	1	3	X
Fuel Manifold		1			
Fuel Mixer		1	4		
Fuel Cavity	1	1	1		X
Lox Dome Structure				4	4
Fuel Manifold Structure				4	4
Chamber at Injector Face		2			
Chamber Wall – x in downstream	5	2			
Chamber Wall – y in downstream	1	1			
IGNITER					
Lox Inlet		1	1		
Lox Manifold		1	1		
Fuel Inlet		1	1		
Fuel Manifold		1	1		
Spark Plug – 1					
Spark Plug – 2					

Table 13. Combustion chamber instrumentation recommendations.

	TCA Testing				
	High Freq Pressure	Static Pressure	Temp	Accel	Strain Gauge
Forward Manifold		2	1	3	
Aft Manifold	2	2	1	3	
JACKET					
Aft of throat					3
Forward of throat					3
Structural support					3
Pc at Chamber Wall					
x inches from Injector Face	5	2			
y inches from Injector Face	1	1			

Table 14. Nozzle instrumentation recommendations.

	TCA Testing					
	High Freq Pressure	Static Pressure	Temp	Accel	Dynamic Strain	Static Strain
Skirt Hot Wall	TBD	30	30			
Skirt Outer Wall			21	10	10	
Nozzle Coolant		12	30			
Coolant Manifold		8	8	3		8
Film Injector		8	8			
Attachment Cone/Flange			12	4	10	10

Table 15. Injector error factors.

Uncertainty	Effect
Venturi Cd Estimate	Calculation of Propellant Flow Rates
Lox Property Data	Flowrates and ODE C^*_{THEOR} Calculations
H_2 Property Data	Flowrates and ODE C^*_{THEOR} Calculations
Chamber Throat Cd Estimate	C^*_{TEST} Calculation
Pc_{THROAT} Estimate from Pc_{FACE}	C^*_{TEST} Calculation
Heat Lost to Chamber Coolant from Injector Face to Throat Estimate	C^*_{TEST} Calculation

Table 16. Chamber error factors.

Uncertainty	Effect
Venturi Cd Estimate	Coolant Flow Rate Calculations
H_2 Property Data	Heat Transfer Calculations
Chamber Dimensions	Heat Transfer Calculations
Accelerometer Data	Vibrational Load Assessment
Hot Gas Transport Property Data	Heat Transfer Calculations

Table 17. Nozzle error factors.

Uncertainty	Effect
Venturi Cd Estimate	Flow Rate Calculations
H_2 Property Data	Flow Rate Calculations and ODE Predictions
Boundary Layer Thickness	Flow Rate and Performance Calculations
Exhaust Gas Properties	Heat Transfer Calculations
Thrust	Performance Verification
Coolant Temperature/Properties (Ambient H_2 for TCA, Hot Gas for Engine)	Cooling Performance Predictions
Coolant Induced Shocks	Performance Calculations and Localized Heating

Table 18. Parameters to be varied during TCA testing.

Factor	Nominal	Level 1	Level 2
A Pc, FACE	2,318 psi (15.98 MPa)	2,270 psi (15.65 MPa)	2,370 psi (16.34 MPa)
B O/F	6.99	6.7	7.2
C Injector Fuel Temp	199 R (110.6 K)	218 R (121.1 K)	160 R (88.9 K)
D CC Coolant Inlet Press	3,685 psi (25.41 MPa)	3,798 psi (26.19 MPa)	3,572 psi (24.63 MPa)
E CC Coolant Flow Rate	47 lbm/s (21.3 kg/s)	49.8 lbm/s (22.6 kg/s)	44.2 lbm/s (20.0 kg/s)
F CC Coolant Inlet Temp	199 R (110.6 K)	186 R (103.3 K)	212 R (117.8 K)
G Nozzle Coolant Flow Rate	66 lbm/s (29.9 kg/s)	69.6 lbm/s (31.6 kg/s)	62.4 lbm/s (28.3 kg/s)
H Nozzle Flow Split	50/10 lbm/s (22.7/4.5 kg/s)	40/5 lbm/s (18.1/2.3 kg/s)	60/15 lbm/s (27.2/6.8 kg/s)

Level 1 = Lower Risk
Level 2 = Higher Risk

Table 19. Taguchi L16 TCA test matrix.

	A 1	B 2	– 3	G 4	AG 5	BG 6	C 7	H 8	AH 9	BH 10	D 11	– 12	E 13	F 14	– 15
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2
3	1	1	1	2	2	2	2	1	1	1	1	2	2	2	2
4	1	1	1	2	2	2	2	2	2	2	2	1	1	1	1
5	1	2	2	1	1	2	2	1	1	2	2	1	1	2	2
6	1	2	2	1	1	2	2	2	2	1	1	2	2	1	1
7	1	2	2	2	2	1	1	1	1	2	2	2	2	1	1
8	1	2	2	2	2	1	1	2	2	1	1	1	1	2	2
9	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
10	2	1	2	1	2	1	2	2	1	2	1	2	1	2	1
11	2	1	2	2	1	2	1	1	2	1	2	2	1	2	1
12	2	1	2	2	1	2	1	2	1	2	1	1	2	1	2
13	2	2	1	1	2	2	1	1	2	2	1	1	2	2	1
14	2	2	1	1	2	2	1	2	1	1	2	2	1	1	2
15	2	2	1	2	1	1	2	1	2	2	1	2	1	1	2
16	2	2	1	2	1	1	2	2	1	1	2	1	2	2	1

Table 20. Preliminary TCA test matrix.

	Pc FACE (psi)	O/F	Injector Fuel Temp (R)	CC Coolant Inlet Press (psi)	CC Coolant Flow Rate (lbm/s)	CC Coolant Inlet Temp (R)	Nozzle Coolant Flow Rate (lbm/s)	Nozzle Flow Split
1	2,270	6.7	218	3,798	49.8	186	70	40/5
2	2,270	6.7	160	3,798	44.2	212	62	40/5
3	2,270	7.2	160	3,572	49.8	212	70	40/5
4	2,270	7.2	218	3,572	44.2	186	62	40/5
5	2,370	6.7	160	3,572	44.2	186	70	40/5
6	2,370	6.7	218	3,572	49.8	212	62	40/5
7	2,370	7.2	218	3,798	44.2	212	70	40/5
8	2,370	7.2	160	3,798	49.8	186	62	40/5
9	2,270	6.7	218	3,572	44.2	212	70	60/15
10	2,270	6.7	160	3,572	49.8	186	62	60/15
11	2,270	7.2	160	3,798	44.2	186	70	60/15
12	2,270	7.2	218	3,798	49.8	212	62	60/15
13	2,370	6.7	160	3,798	49.8	212	70	60/15
14	2,370	6.7	218	3,798	44.2	186	62	60/15
15	2,370	7.2	218	3,572	49.8	186	70	60/15
16	2,370	7.2	160	3,572	44.2	212	62	60/15

Table 21. Preliminary injector TCA stability test matrix.

	Pc FACE (psi)	O/F	Injector Fuel Temp (R)	Bomb*
1	1,580	6.82	218	yes
2	1,580	6.82	174	yes
3	2,318	6.7	218	yes
4	2,318	6.7	199	yes
5	2,318	6.99	218	yes
6	2,318	6.99	199	yes
7	2,318	6.99	160	yes
8	2,318	7.3	199	yes
9	2,318	7.3	160	yes
10	2,430	6.7	218	yes
11	2,430	6.99	218	yes
12	2,430	6.99	199	yes
13	2,430	6.99	160	yes
14	2,430	7.3	199	yes
15	2,430	7.3	160	yes

* Detonate two bombs per test, during early mainstage
Conduct test matrix for two injectors
Bomb size determined prior to initiation of this test series

Table 22. NASA SP-194 and CPIA 247 stability test recommendations.

	NASA SP-194 Recommendation	CPIA 247 Recommendation
Bomb Grain Size	Multiple Sizes 50 to 100 percent of mean Pc overpressure	At Least 3 Sizes 10 to 100 percent of mean Pc overpressure
Bomb Location	Minimum of Three Locations* (1) Radially between wall and mid-radius of chamber and axially one quarter of the distance to the throat (2) Radially between wall and axially in the convergent throat section (3) Radially on the chamber centerline and axially not further from injector than one quarter of distance from injector to throat	Multiple Locations Both from injector face to convergent section of chamber throat, and in different radial and circumferential locations on the injector face
Chamber Type	Solid walled or cooled metal wall Engine tests must be done with flight configuration chamber	Solid walled or cooled metal wall
Test Conditions	Five conditions of Pc and O/F in steady-state operation. Max and min conditions defined as estimated extremes of operation in flight	Range of Pc, O/F and propellant temperatures from 10 percent below expected low operating point to 10 percent above expected high. Throttle transient and shutdown transient tests recommended
Number of Units	Initial screening: each injector candidate type Candidate evaluation: at least one injector Prototype verification: each of two injectors Engine verification: each of two engines	At least three injector units and two complete engines. Engines with different accumulations of time should be tested to determine whether engine stability deteriorates with time
Stability Criteria	Injector stable if: Amplitudes of driven oscillations resulting from all bomb tests attenuate to 5 percent of mean Pc within 40 ms.	Injector stable if: Pc oscillations between 10 and 10,000 Hz damp to 10 percent of mean Pc within $1{,}250/\sqrt{f}$ ms. At least two bombs must be detonated at each specified test condition.

* Prime location is on injector face near chamber wall, but a few tests should be made to eliminate possibility of any location anomaly

Table 23. Recommended STME injector stability test conditions.

Bomb Grain Size	Multiple sizes including 10 grain Rational: CPIA 247 and NASA SP-197.
Bomb Location	Two locations on injector face. No bomb locations along chamber. Rational: Analysis indicated that only tangential mode of instability significant, therefore only bombs on injector face are required. LSI testing in similar locations will provide additional data. In addition, bomb locations along regen cooled chambers are difficult to provide.
Chamber Type	Metal wall - regen cooled or heat sink Rational: CPIA 247 and NASA SP-194 recommendations
Test Conditions	Component Level: Range of Pc, O/F, and Tf, including tests below lowest planned and highest planned engine operating points. Rational: CPIA 247 and NASA SP-194 recommendations Engine Level: Range of Pc, O/F, and Tf, including transient tests. Rational: CPIA 247 and NASA SP-194 recommendations
Number of Units	Component Level: 2 units Rational: CPIA 247 and NASA SP-197 recommendations. Two units rather than three recommended due to LSI and modified LSI testing. Engine Level: 2 units Rational: CPIA 247 and NASA SP-197 recommendations
Stability Criteria	Pc oscillations between 10 and 10,000 Hz must damp to 10 percent of mean Pc within $1{,}250/\sqrt{f}$ ms. Two bomb detonations at each specified test condition Rational: CPIA 247 and NASA SP-197 recommendations

Table 24. Number of TCA hot fire tests.

Bomb Size Determination for One (1) Unit	= 10
Injector Stability Testing for Two (2) Units	2 X 15 = 30
TCA Ignition and Check Out Tests	= 6
TCA Taguchi Test Matrix for One (1) Unit	1 X 16 = 16
Additional TCA Tests for One (1) Unit 1 Test at each of the following conditions: - STME Nominal - STME Throttle - 3 Sigma - STME Throttle - 80% Flight Effects + 3 Sigma	1 X 4 = 4
TOTAL	= 66

APPENDIX

The equation used to calculate the injector ηC^* is defined as follows:

$$\eta C^* = \frac{(Pc_{TH\ STAG})\,(Cd)\,(At)\,g}{C^*_{THEOR}\,(\omega_{LOX} + \omega_{H2})}$$

where:
$Pc_{TH\ STAG}$ = throat stagnation pressure = 2,250 psi
Cd = chamber throat discharge coefficient = 0.981
At = area of the chamber throat = 149.45 in^2
g = gravitational constant = 32.17 $\frac{lbm\text{-}ft}{lbf\text{-}s^2}$
C^*_{THEOR} = theoretical C* = 7411 ft/s
ω_{LOX} = LOX flow rate = 1266 lbm/s
ω_{H2} = Hydrogen flow rate = 181 lbm/s

The values listed above are for the nominal 2,250 Pc, 6.99 O/F case listed in Power Balance 26b (ref. 4). An estimated error in $Pc_{TH\ STAG}$ and the propellant flow rates of ±1 percent was chosen. An error of ±0.5 percent was estimated for Cd. The Power Balance lists both an aerodynamic throat area and a geometric throat area. The difference between the two values is 2.84 in^2 or 1.9 percent. This 1.9-percent difference was chosen as the error on the low side (–1.9 percent). A value of 0.5 percent was chosen for a high error. No errors in g, C^*_{THEOR}, or propellant property data were estimated.

If all the variables were high by their error:
$\eta C^* = 0.9996$

If all the variables were low by their error:
$\eta C^* = 0.966$

These values lead to the range in anticipated ηC^* of 97 to 100 percent. With all nominal values used the ηC^* equals 98.96 percent.

APPROVAL

DESIGN VERIFICATION TEST MATRIX DEVELOPMENT FOR THE STME THRUST CHAMBER ASSEMBLY

By Carol E. Dexter, Sandra K. Elam, and David L. Sparks

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

J.P. McCarty
Director, Propulsion Laboratory

☆ U. S. GOVERNMENT PRINTING OFFICE 1993 733–050 6 80077